EXPERIMENTAL ANALYSIS OF MANIPULATOR JOINTS LOADING IN HYDRAULIC EXCAVATORS

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Abstract: The paper provides a procedure for experimental determination of loading to which elements of kinematic pairs (joints) of the kinematic chain and drive mechanisms in an excavating manipulator of hydraulic excavators with continuous tracks are subjected. A mathematical model is defined to enable the determination of force and moment vectors of joints loading, on the basis of the measured quantities of the excavator state during the operation in exploitation conditions. The measured quantities of the excavator state relate to the position of the kinematic chain and the pressures of the hydraulic system in the ducts of the excavator drive mechanisms actuators. As an example, the paper provides research results obtained during experimental determination of loading of kinematic pairs (joints) in a hydraulic excavator of 17,000 kg in mass.

Keywords: hydraulic excavators, manipulator joints loading

1. INTRODUCTION

The primary function of hydraulic excavators, of all sizes, is the cyclic transport of various materials in the variable working range. It is characteristic that operating cycles of hydraulic excavators consist in repeating the following operations: excavating the material, transporting the material from the plane of excavation to the plane of unloading, unloading the material and returning to the plane of excavation. The structural support of the excavator operating cycle is the kinematic chain of the general configuration comprising the support and movement mechanism, the rotating platform and the multi-member manipulator which can be equipped with various tools for performing different functions. Members of the manipulator kinematic chain form kinematic pairs connected by fifth-class rotary joints. Drive mechanisms of kinematic chain members in an excavator manipulator are constructed using hydraulic actuators: hydraulic motors or two-way hydraulic cylinders.

The research conducted in this area relate to: a) analytical modelling and experimental determination of load during the digging process [1][2], b) development of mathematical models for kinematic and dynamic excavator analysis [3][4], c) development of drive mechanisms and control systems [5-7], and d) definition of indicators for analysis and evaluation of excavator digging efficiency [8].

The aim of the paper is to analyse the loading to which members and joints of the kinematic chain of an excavator manipulator are subjected during the operating cycle of the machine, so as to determine the size and character of changes in loading that are relevant for their reliable dimensioning.

2. MATHEMATICAL MODEL

In this paper a mathematical model is developed to determine the loading of kinematic pairs (joints) and members of the excavating manipulator in hydraulic excavators, based on the measured quantities of the state of the kinematic chain and drive mechanisms of the excavator Table 1, Figure 1, during the operation of the machine in exploitation conditions.

The mathematical model encompasses the general five-member configuration of the excavator which comprises: the support and movement member L₁ Figure 1a, the rotating platform L₂, and the three-member planar manipulator with: the boom L₃, stick L₄ and tool L₅ in the form of a digging bucket with a specific capacity.

The members of the kinematic chain of the excavator form fifth-class pairs – rotary joints with a single degree of freedom. Axes of joints are the axes of relative turning (rotation) of the members which constitute the kinematic pairs of the chain. The support and movement member of the excavator and the support surface form a third-class zero joint with potential movements in the plane of the surface. The kinematic chain of the manipulator considered in the excavator model is of planar configuration. The axes of joints are parallel, while the centres of the manipulator joints Oᵢ (i=3,4,5) lie in the same plane – the plane of the manipulator. The
intersection of the bucket cutting edge through the plane of the manipulator represents the centre of the bucket cutting edge $O_w$.

Elements of fifth-class rotary joints of drive mechanisms of the excavator manipulator are derived in the form of a single pair of sliding shells 1 Figure 1b, embedded in the hub of the relatively mobile member $L_i$ and the clevis pin 2 linked to the relatively immobile member $L_{i-1}$ of the kinematic pair. Basic dimensions of the joint are: the diameter of the clevis pin (shaft) $d_{si}$, the width of the sliding shell $b_{si}$, the diameter of the hub $D_{si}$, the span of the shells $l_{si}$, and the span of the hub $L_{si}$.

The assumptions of the mathematical model of the excavator kinematic chain are:

- The support surface and kinematic chain members are modelled using rigid bodies,
- the contact between the support and movement member and the excavator support surface is taken as the first joint which has a variable position and form, thus having the form of a translatory-sliding joint along the contact between the support and movement member and the surface, while having the form of rotary joints $O_{11}, O_{12}$, whose axes represent potential (longitudinal x-x or transverse z-z) Figure 1a, excavator rollover lines,
- during the manipulation task, the kinematic chain of the excavator is subjected to gravitational, innate and external (technological) forces – digging resistances $W$,
- the position of the mass centre of a hydraulic cylinder is in the middle of the current length of that hydraulic cylinder,
- friction resistances are neglected in the joints of the kinematic chain and drive mechanisms of the excavator.

The area of the excavator model is determined by an absolute coordinate system $OXYZ$ Figure. 1a with unit vectors $\hat{k}_i, \hat{j}_i, \hat{i}_i$ along the coordinate axes. The excavator support surface lies in the horizontal OXZ plane of the absolute coordinate system, while the vertical OY axis of the same system falls on the axis of the support member-rotation member kinematic pair when the excavator is positioned on the horizontal surface.

A member of the kinematic chain $L_i$, in its local coordinate system $O_i x_i y_i z_i$, with unit vectors $\hat{i}_i, \hat{j}_i, \hat{k}_i$ along the coordinate axes, is defined by geometric, kinematic and dynamic parameters encompassed in the set:

$$ L_i = \{ \hat{e}_i, \hat{s}_i, \hat{t}_i, m_i, \hat{I}_i \} \quad (1) $$

where: $\hat{e}_i$ – the unit vector of joint $O_i$ axis which connects member $L_i$ to the previous member $L_{i-1}$ Figure 1a, $\hat{s}_i$ – the vector of the position of joint $O_{i+1}$ centre which is used to connect the chain member $L_i$ to the next member $L_{i+1}$ (vector magnitude $s_i$ represents the kinematic length of the member), $\hat{t}_i$ – the vector of the position of the member $L_i$ mass centre, $m_i$ – the member mass, $\hat{I}_i$ – the tensor of the moment of inertia of the member.

Vector quantities marked with caps relate to the local coordinate system, while those without caps relate to the absolute coordinate system.

The internal (generalized) coordinates of the mathematical model of the excavator kinematic chain are represented by angles $\theta$ of the relative position of member $L_i$ in relation to the previous member $L_{i+1}$ upon rotation around the joint $O_i$ axis. The lifting angle of
the movement mechanism $\theta_i$ is determined on the basis of the measured relative vertical movement $c_1$ of the support and movement member $L_1$, in relation to the support surface. Angles $\theta_i$ (i=3,4,5) of the relative position of the manipulator member $L_i$ in relation to the previous member $L_{i-1}$ are determined depending on the measured length $c_i$ of the hydraulic cylinders of the manipulator boom, stick and bucket drive mechanisms.

Unit vector $e_i$ of joint $O_i$ axis of the excavator kinematic pair in the absolute coordinate system is determined using the equation:

$$
e_i = A_{ii} \hat{e}_i$$  \hspace{1cm} (2)

Unit vector $e_1$ of the first joint axis is directed along the potential (longitudinal x-x or transverse z-z) Figure 1a, excavator rollover lines.

Vector $\tau$ of joint $O_i$ centre of the excavator kinematic pair in the absolute coordinate system is determined using the equation:

$$\tau = \sum_{i=1}^{i-1} A_{ii} \hat{s}_i \quad \forall \ i=2,3,4,5$$  \hspace{1cm} (3)

Vector $\tau_w$ of the centre of the bucket cutting edge in the absolute coordinate system is determined using the equation:

$$\tau_w = \sum_{i=1}^{i} A_{ii} \hat{s}_i$$  \hspace{1cm} (4)

Vectors $\tau_{ii}$ of the centre of the excavator kinematic chain member $L_i$ mass in the absolute coordinate system are determined using the equation:

$$\tau_{ii} = \tau + A_{ii} \hat{s}_i$$  \hspace{1cm} (5)

where: $A_{ii}$ – the transfer matrix used to transfer the vector quantities from the local coordinate system $O_i x_i y_i z_i$ of member $L_i$ to the absolute coordinate system OXYZ.

Kinematic quantities for the centre of the chain member $L_i$ mass are: linear $v_i$ and angular $\omega_i$ velocity and linear $w_i$ and angular $\varepsilon_i$ acceleration, where the movement of the previous member $L_{i-1}$ is taken as transferable, while the movement of the observed member $L_i$ in joint $O_i$ is taken as relative.

To determine the kinematic quantities of the chain member $L_i$ in relation to the absolute coordinate system, recursive equations are used [9]:

$$v_i = v_{i-1} + \dot{\theta}_i e_i$$  \hspace{1cm} (6)

$$\omega_i = \omega_{i-1} + \dot{\omega}_i + (\dot{\omega}_{i-1} \times \omega_{i-1}) + (\omega_{i-1} \times t_i)$$  \hspace{1cm} (7)

$$w_i = w_{i-1} + (\dot{\varepsilon}_{i-1} \times (s_{i-1} - t_{i-1})) + (\varepsilon_{i-1} \times \omega_{i-1}) + (\omega_{i-1} \times t_i)$$  \hspace{1cm} (8)

where: $\dot{\theta}_i, \dot{\omega}_i$ – the angular velocity and angular acceleration of member $L_i$ in joint $O_i$.

Dynamic quantities of member $L_i$ are: innate force $F_i$, which is determined by Newton’s second law:

$$F_i = -m_i w_i$$  \hspace{1cm} (10)

the moment of innate forces $M_{ii}$, which is determined on the basis of Euler’s dynamic equations:

$$M_{ii} = -I_i \ddot{\varepsilon}_i + (\dot{\omega}_i \times I_i \ddot{\omega}_i); \quad M_{ii} = A_{ii} M_{ii}$$  \hspace{1cm} (11)

The total force related to the centre of member $L_i$ mass, taking into account the influence of gravity, is equal to:

$$F_{ii} = F_i - m_i g j$$  \hspace{1cm} (12)

Bearing in mind the assumption that the vector of digging resistance $W$ acts in the centre of the bucket cutting edge, the fictive interruption of the manipulator kinematic chain in two different joints $O_i$ and $O_j$ (i\neq j, i,j=2,3,4,5) can set the equilibrium conditions, for the removed chain parts, which can used to determine the vector of resistance $W$ on the basis of the measured quantities of the excavator state during the operation in exploitation conditions [10].

Force $F_i$ Figure 1c and moment $M_{ii}$ of the loading of the elements of joint $O_i$ Figure 1b, are determined by using the fictive interruption in the manipulator kinematic chain in the same joint, and by reducing all of the loads of the given part of the chain to the centre of the joint ($j>i$) using the equations:

$$F_i = F_i + W + \sum_{j=i+1}^{5} F_{ju} \quad \forall \ i=3,4,5$$  \hspace{1cm} (13)

$$M_{ii} = M_{ii} + (r_i - r_i) \times W + \sum_{j=i+1}^{5} M_{ju} + \sum_{j=i+1}^{5} (r_{ij} - r_{ij}) \times F_{ju} \quad \forall \ i=3,4,5$$  \hspace{1cm} (14)
where: $F_{ic}$ — the force in the hydraulic cylinder of the drive mechanism, $M_{ic}$ — the moment of the drive mechanism, $W$ — the potential digging resistance.

The force $F_{ic}$ and moment $M_{ic}$ quantities of drive mechanisms of the excavator manipulator are determined using the equations:

$$F_{ic} = \eta_{cmi} \cdot \pi \cdot \frac{d_i^4 - d_i^2 \pi^4}{4} \cdot p_{i1} \cdot \forall i = 3,4,5$$

$$M_{ic} = \text{sign}(k_i) \cdot F_{ic} \cdot \forall i = 3,4,5, \quad k_1 = 1, \quad k_3 = k_5 = -1$$

where: $n_{ic}$ — the number of hydraulic cylinders in the drive mechanism, $p_{i1}, p_{i2}$ — the measured pressure in the hydraulic cylinder on the piston side and on the connecting rod side of the drive mechanism, $\eta_{cmi}$ — the mechanical degree of efficiency of the hydraulic cylinder, $r_{ic}$ — the transmission function of the drive mechanism of the excavator manipulator [9].

Components of force $F_{ir}$ and moment $M_{ir}$ of the loading of joint $O_i$ of the excavator kinematic chain in the local coordinate system of member $L_i$:

$$\bar{F}_{ir} = A_{oi} \bar{F}_{ri}, \quad \bar{F}_{ir} = A_{oi} \bar{F}_{ri}, \quad \bar{F}_{ir} = A_{oi} \bar{F}_{ri}, \quad \bar{F}_{ir} = A_{oi} \bar{F}_{ri}, \quad i = 3,4,5$$

$$\bar{M}_{ir} = A_{oi} \bar{M}_{ri}, \quad \bar{M}_{ir} = A_{oi} \bar{M}_{ri}, \quad \bar{M}_{ir} = A_{oi} \bar{M}_{ri}, \quad \bar{M}_{ir} = A_{oi} \bar{M}_{ri}, \quad i = 3,4,5$$

where: $A_{oi}$ — the transfer matrix used to transfer the vector quantities from the absolute coordinate system OXYZ to the local coordinate system $O_i x_i y_i z_i$ of member $L_i$. During the manipulation task, the drive moment of mechanism $M_{ic}$ overcomes the components of loading moments which are collinear with the joint $e_i = k_i$ axis, thus the resulting moment for the joint $O_i$ axis is equal to $\bar{M}_{ir} = 0$, while the other components of joint loads strain the joint structure, and some even cause friction between its elements.

3. PROGRAM

According to the previously defined mathematical model for determining the loading of kinematic pairs (joints) of the manipulator, it is necessary to measure the quantities of state Table T1, Figure 1, of the excavator kinematic chain and drive mechanisms in operation under real-exploitation conditions.

A program is developed to process and analyze the measured quantities using a computer. By employing the measured quantities $c_i, p_{i1}, p_{i2}$ as input data, the program first determines, in the function of the duration of the operating cycle, the geometric and kinematic quantities: generalized coordinates $\theta_i$, coordinates of joint centres and mass centres of chain members, angular velocities $\dot{\theta}_i$ and angular accelerations $\ddot{\theta}_i$, and linear $v_i$ and angular $\omega_i$ velocity and linear $w_i$ and angular $\varepsilon_i$ acceleration for the mass centre of the excavator kinematic chain members.

Table 1. Measured quantities of the state of the excavator kinematic chain and drive mechanisms

<table>
<thead>
<tr>
<th>Measuring spot</th>
<th>Name of the measured quantity</th>
<th>Symbol</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Lifting of the support and movement mechanism</td>
<td>$c_1$</td>
<td>m</td>
</tr>
<tr>
<td>M2</td>
<td>Platform rotation angle</td>
<td>$c_2$</td>
<td>$^\circ$</td>
</tr>
<tr>
<td>M3</td>
<td>Boom hydraulic cylinder motion</td>
<td>$c_3$</td>
<td>m</td>
</tr>
<tr>
<td>M4</td>
<td>Stick hydraulic cylinder motion</td>
<td>$c_4$</td>
<td>m</td>
</tr>
<tr>
<td>M5</td>
<td>Bucket hydraulic cylinder</td>
<td>$c_5$</td>
<td>m</td>
</tr>
<tr>
<td>M6</td>
<td>Pressure in one duct of the hydraulic motor for platform rotation drive</td>
<td>$p_{21}$</td>
<td>MPa</td>
</tr>
<tr>
<td>M7</td>
<td>Pressure in the other duct of the hydraulic motor for platform rotation drive</td>
<td>$p_{22}$</td>
<td>MPa</td>
</tr>
<tr>
<td>M8</td>
<td>Pressure in the boom hydraulic cylinder on the piston side</td>
<td>$p_{31}$</td>
<td>MPa</td>
</tr>
<tr>
<td>M9</td>
<td>Pressure in the boom hydraulic cylinder on the connecting rod side</td>
<td>$p_{32}$</td>
<td>MPa</td>
</tr>
<tr>
<td>M10</td>
<td>Pressure in the stick hydraulic cylinder on the piston side</td>
<td>$p_{41}$</td>
<td>MPa</td>
</tr>
<tr>
<td>M11</td>
<td>Pressure in the stick hydraulic cylinder on the connecting rod side</td>
<td>$p_{42}$</td>
<td>MPa</td>
</tr>
<tr>
<td>M12</td>
<td>Pressure in the bucket hydraulic cylinder on the piston side</td>
<td>$p_{51}$</td>
<td>MPa</td>
</tr>
<tr>
<td>M13</td>
<td>Pressure in the bucket hydraulic cylinder on the connecting rod side</td>
<td>$p_{52}$</td>
<td>MPa</td>
</tr>
</tbody>
</table>

Quantities of angular velocities and angular accelerations of the excavator kinematic chain members are determined on the basis of the double numerical differentiation using the equations:

$$\dot{\theta}_i = \frac{\theta_{i(t+2\Delta t)} - \theta_{i(t-2\Delta t)}}{4\Delta t}$$

$$\ddot{\theta}_i = \frac{\theta_{i(t+\Delta t)} + \theta_{i(t-\Delta t)} - 2\theta_{i(t)}}{2\Delta t}$$

where: $\theta_{00}$ — the generalized coordinate in the moment $t$ of the duration of the digging operation, $\theta_{0\Delta t}, \theta_{02\Delta t}, \theta_{03\Delta t}, \theta_{04\Delta t}, \theta_{05\Delta t}$ — the generalized coordinates (angles) in the moment of time which is larger or smaller for one or two intervals of time $\Delta t$ than time $t$, $\Delta t$ — the interval of time between the two subsequent measurements of quantities.
The program further determines the transfer functions $c_i$ and drive moments $M_i$ of individual drive mechanisms on the basis of the quantity parameters of actuators $d_{i1},d_{i2}$ and measured pressures $p_{i1},p_{i2}$ in their working ducts. Finally, after determining the innate forces $F_i$ and moment $M_i$ of chain members, the program determines the vector of digging resistance $W$ and components of forces $F_i$ and moments $M_i$ of the loading of joints $O_i$ ($i=3,4,5$) of the kinematic chain of the excavator manipulator.

As an example, the determination and analysis of the loading of the kinematic chain joints was performed on the basis of the testing results of an excavator with continuous tracks, of 17,000 kg in mass and 70 kW in power, equipped with an excavating bucket of 0.6 m$^3$ in volume. The sampling of measured quantities was conducted in the time interval $\Delta t=0.032$ s. During the testing, forty-two full cycles were measured with different manipulation tasks within the entire working range of the excavator. Out of the total number of measurements, here separated and analysed are the measurements conducted during the digging cycle of a canal with the maximum depth of around 1.2 m and equal in width to the bucket, which corresponds to the measured quantities given in the diagrams that show the change in: the movement of the support and movement mechanism $c_1$ Figure 2a, the angle of platform rotation $\theta_2$, and the motion of hydraulic cylinders $c_3,c_4,c_5$, and pressures $p_{i1},p_{i2}$ Figure 2b,c ($i=2,..,5$) in the ducts of the excavator drive mechanisms actuators.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Measured quantities of the excavator state: a) movement of the movement mechanism $c_1$, angle of the platform movement $\theta_2$ and motions of hydraulic cylinders $c_3,c_4,c_5$ of the manipulator, b, c) pressures $p_{i1},p_{i2}$ in excavator drive mechanisms actuators}
\end{figure}

Out of the determined quantities, obtained by using the developed program, the paper shows the change in the quantities of the components of force Figure 3a,4a,5a, and moment Figure 3b,4b,5b, of the loading of joints $O_3$, $O_4$ and $O_5$ of the kinematic chain of the manipulator during the operating cycle of the excavator.

The diagram of the resulting force $\mathbf{F}$ Figure 3a, in joint $O_3$ of the kinematic chain of the excavator manipulator, and its components $\mathbf{F}_{x3},\mathbf{F}_{y3},\mathbf{F}_{z3}$ shows that the resulting force and its components have the highest value during the material transport operation, when the boom lifts simultaneously with the rotation of the platform with a full bucket of the material. It is characteristic that components $\mathbf{F}_{x3}$ and $\mathbf{F}_{y3}$ have an alternating loading character during the excavation operation and the operation of returning to...
the new digging position. Component $F_{iz}$ is significantly smaller than the other components and its alternating value occurs at the beginning of the platform rotation towards the plane of unloading and at the beginning of the platform rotation towards the new plane of excavation.

![Figure 3](image.png)

**Figure 3.** Loading of the kinematic pair (joint) $O_i$ of the kinematic chain of the excavating manipulator in hydraulic excavators:
- a) components of loading forces of the joint,
- b) components of loading moments of the joint

Also, component $M_{iz}$ Figure 3b, of the moment of the loading of joint $O_i$ has the most prominent oscillatory changes at the beginning of the platform rotation towards the plane of unloading and at the beginning of the platform rotation towards the new plane of excavation with an empty bucket, where it reaches the maximum value. Component $M_{iz}$ of the loading of joint has a smaller value with a characteristic change in the loading when the full bucket exits the pit (canal) and at the beginning of the material transport.

![Figure 4](image.png)

**Figure 4.** Loading of the kinematic pair (joint) $O_i$ of the kinematic chain of the excavating manipulator in hydraulic excavators:
- a) components of loading forces of the joint,
- b) components of loading moments of the joint

Also, component $M_{iz}$ Figure 3b, of the moment of the loading of joint $O_i$ has the most prominent oscillatory changes at the beginning of the platform rotation towards the plane of unloading and at the beginning of the platform rotation towards the new plane of excavation with an empty bucket, where it reaches the maximum value. Component $M_{iz}$ of the loading of joint has a smaller value with a characteristic change in the loading when the full bucket exits the pit (canal) and at the beginning of the material transport.
The diagram of the resulting force $\mathbf{F}$ Figure 4a, in joint $O_4$ of the kinematic chain of the excavator manipulator, and its components $\mathbf{F}_{x_4}, \mathbf{F}_{y_4}, \mathbf{F}_{z_4}$ shows that the resulting force and its components have the highest value during the excavation operation. Component $\mathbf{F}_{x_4}$ is negligible in comparison to components $\mathbf{F}_{y_4}, \mathbf{F}_{z_4}$ which act in one direction during the excavation operation, and then in the opposite direction after the excavation operation.

![Diagram](image)

**Figure 5.** Loading of the kinematic pair (joint) $O_5$ of the kinematic chain of the excavating manipulator in hydraulic excavators: a) components of loading forces of the joint, b) components of loading moments of the joint

Component $\mathbf{M}_{x_5}$ Figure 4b, of the moment of loading has the highest value at the beginning of the platform rotation towards the new plane of excavation with an empty bucket, and it is significantly larger than component $\mathbf{M}_{y_5}$ of the moment of loading which has an alternating loading character of small magnitude. The diagram of the resulting force $\mathbf{F}$ Figure 5a, in joint $O_5$ of the kinematic chain of the excavator manipulator, and its components $\mathbf{F}_{x_5}, \mathbf{F}_{y_5}, \mathbf{F}_{z_5}$ shows that the resulting force and its components have the highest value during the excavation operation and are of significantly larger magnitude in comparison to component $\mathbf{F}_{z_5}$.

Characteristic small magnitude changes in forces of joint $O_5$ occur during the material unloading operation. The change in magnitude of moment components $\mathbf{M}_{x_5}, \mathbf{M}_{y_5}$ of the loading of joint $O_5$ Figure 5b, occurs during the transport of the material, the rotation of the platform, and at the very beginning of the operation of returning the empty bucket to the new plane of excavation. The comparative analysis of the loading of kinematic chain joints in a hydraulic excavator shows that the maximal forces do not occur during the same cycle operations, however, the magnitude of the forces in joints $O_3$ and $O_5$ is almost twice the size of the magnitude in joint $O_5$. On the other hand, the maximal values of the loading moment of joints occur during the same cycle operations, but the magnitude, for example, of the moments in joint $O_3$ is ten times greater than the moments of the loading of joint $O_5$.

**CONCLUSION**

The conducted research, whose part is presented in this paper, represent a contribution to the analysis of defining the character of change in the loading of kinematic pairs (joints) of the kinematic chain of an excavating manipulator in hydraulic excavators. Research results show that the elements of kinematic pairs (joints) of the kinematic chain of an excavating manipulator are subjected to the alternating influence of forces and moments. The importance of knowledge of joint loading vectors is the basis of necessary structural analyses with the aim of optimization, reliability and life cycle of the structure of the kinematic chain members of the manipulator and drive mechanisms of the excavator. The developed software and the set of measured quantities obtained during the conducted testing of the hydraulic excavator can be used not only to define the joint loading vectors but also for other dynamic analyses of the excavator.
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